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GRAIN PRESSURE IN A MODEL SILO AS AFFECTED BY MOISTURE CONTENT INCREASE

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A b s t r a c t. Swelling pressure of wetted grain was measured in a model silo. Experimental set was designed to simulate the conditions under which grain is subjected to wetting by ambient air of the humidity higher than the equilibrium relative humidity corresponding to the existing moisture content of grain. The model involves superposition of two basic kernel reactions to water supply: (i) swelling of kernels, (ii) decrease in kernels elasticity with an increase in the moisture content. The model properly describes the relation between swelling pressure and the increase in the moisture content in a range of the moisture content increase up to 0.02. Swelling pressure of the wetted grain is strongly influenced by the initial bulk density which depends on the precompression history. The experiments performed indicate that distribution and value of the swelling pressure in the model silo is not uniform and depends on the path of wet air movement.

K e y w o r d s: grain, silo, pressure, swelling

INTRODUCTION

Grain stored in silos may become subject to wetting by rainwater ingress or by ambient air of humidity higher than the equilibrium relative humidity corresponding to the existing moisture content of the grain. During the near-ambient drying process, ambient air is blown through the bedding to cool the grain and lower the grain moisture. When the air with a specific temperature and relative humidity is passed through a bed of grain, the grain will either lose or absorb moisture, depending on its equilibrium relative humidity corresponding to the existing moisture content that can be above or below the relative humidity of the drying air [8]. When the grain absorbs moisture, kernels swell, and the grain bulk tends to expand. This expansion is restricted by the silo wall, and consequently the swelling grain imposes additional pressure on the silo wall [1-3,6,8,13]. Changes in the moisture content affect both the properties of an individual kernel and bulk properties of grain, thus affecting bin loads.

There is a big differentiation in the values of swelling pressure reported by various authors. Dale and Robinson [3] investigated the effects of moisture content changes on the pressure of grain in bins. Their test results indicated that when the moisture content of grain was increased by 4 % w.b., the lateral wall pressure increased as much as six times and the vertical floor pressure increased four times. Blight [1] observed that the swelling pressure of wetted grain under constant vertical stress with zero lateral strain may double in value. Kebeli [7] noticed that an increase in the moisture content of 11% d.b. resulted in the five fold increase in the lateral pressure and two fold increase in the vertical pressure. Britton *et al*. [2] monitored vertical forces on the wall of a model bin during the wetting process. After 15 h of wetting the gravitational force due to the grain mass was completely balanced by the upward force of grain swelling. Horabik and Molenda [6] found that the swelling pressure of wetted grain is strongly influenced by the initial bulk density, i.e., it depends on precompression history. The maximum value of the swelling pressure of wheat grain measured in an oedometer after precompression to 0.5 MPa resulting in the initial bulk density of 835 kg m^{-3} was found to be approximately 0.17 MPa, and occurred at the moisture content increase of 0.2.

The objective of this study was to explore the swelling pressure of the wetted grain contained in a model silo. Experiments were performed simulating the behaviour of the grain when subjected to wetting by the ambient air of higher humidity than the equilibrium relative humidity corresponding to the existing moisture content of the grain.

THEORETICAL APPROACH

Zhang and Britton [13] proposed a theoretical model predicting hygroscopic loads in grain storage bins. A volume increase of the wetted grain kernel was assumed to be equal to the volume of water absorbed by the kernel [9]. The volumetric strain of the grain bulk ε_u, caused by the moisture content increase was calculated from the swelling of individual grain kernels:

$$\varepsilon_u = \frac{\Delta V}{V_o} = \frac{\rho_{ko}\Delta u}{(1+u_o)\rho_w} \tag{1}$$

where: u_o - initial moisture content (d.b), Δu - moisture content increase (d.b.), ρ_{ko} - density of kernel (kg m^{-3}), ρ_w - density of water (kg m^{-3}).

Considering the Hertzian type of interactions between individual kernels [10,11], the following relationship between an effective elastic modulus of grain in bulk, K, the confining pressure, p, and the moisture content, u, was postulated by Horabik and Molenda [5]:

$$K(p,u) = K_o E(u)^{\frac{2}{3}} |p|^{\frac{1}{3}} \tag{2}$$

where the modulus of elasticity of kernels, $E(u)$, decreases linearly with an increase in the moisture content [4,12]:

$$E(u) = E(u_o) + \frac{dE}{du}\Delta u \tag{3}$$

where: E - modulus of elasticity of kernels (MPa), dE/du - rate of modulus of elasticity decrease with moisture content increase (MPa), K - effective elastic modulus of grain in bulk (MPa), K_o - packing parameter [11], p - confining pressure (MPa).

The total volumetric strain of grain in bulk, ε_v, is the sum of two independent components: the volumetric strain resulting from confining pressure, ε_c, and the volumetric expansion resulting from swelling of wetted grain, ε_u, (Fig. 1):

$$\varepsilon_v = \frac{p}{K(p,u)} + \frac{\rho_{ko}\Delta u}{(1+u_o)\rho_w}. \tag{4}$$

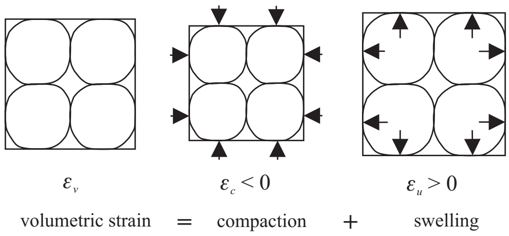

Fig. 1. Illustration of volumetric strain resulting from compaction by confining pressure and kernel swelling.

The following relationship between the confining pressure, p, and the moisture content increase, Δu, can be found from the Eq. (4) in the case of swelling in a rigid container (ε_v=0):

$$|p(\Delta u)| = \left(\frac{K_o \rho_{ko}\Delta u}{(1+u_o)\rho_w}\right)^{\frac{3}{2}} \left(E(u_o) + \frac{dE}{du}\Delta u\right). \tag{5}$$

This function has the maximum for $\Delta u = -3E(u_o)/(5dE/du)$. When kernels swell, the contact forces increase. At the same time the modulus of elasticity decreases. As a consequence, the pressure reaches its maximum value and then decreases.

Approximation of an initial part of the swelling process of wheat, $p(\Delta u)$, closed in a rigid oedometer obtained by Horabik and Molenda [6] is shown in Fig. 2. The model properly predicts the swelling pressure in the range of the moisture content increase of up to 0.02. The maximum of the swelling pressure occurred at the moisture content increase of 0.2.

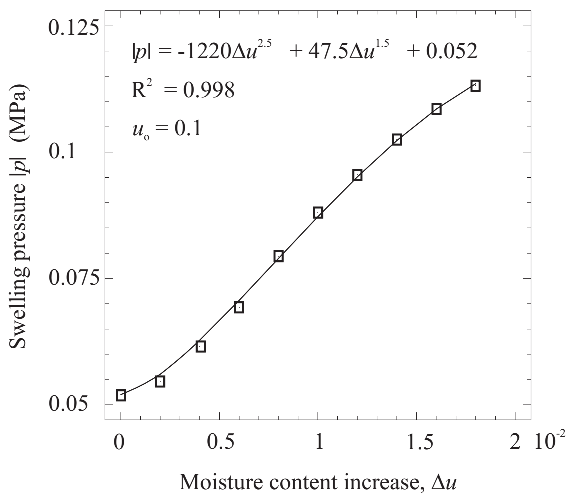

Fig. 2. Approximation of the initial part of the swelling pressure - moisture content increase relation [6].

EQUIPMENT AND PROCEDURE

The model silo was 0.61 m in diameter and 0.75 m in high (Fig. 3). The flat bottom and top cover of the silo consisting of five concentric rings with an equal surface area were used to measure radial distribution of the vertical pressure σ_v. Each ring, and the silo wall, was supported independently on the three load cells separated by an angular distance of 120^o. To measure the mean lateral pressure, σ_n, a galvanised steel cylinder 3 mm thick was constructed in two semicircular halves cut along the axis. The two semicircular halves were connected with four load cells installed in pairs on two connection lines, which restored the cylindrical shape of the wall. This configuration allowed for the determination of vertical pressure distribution on the silo floor and top cover and mean lateral and tangent pressure on the silo wall [6].

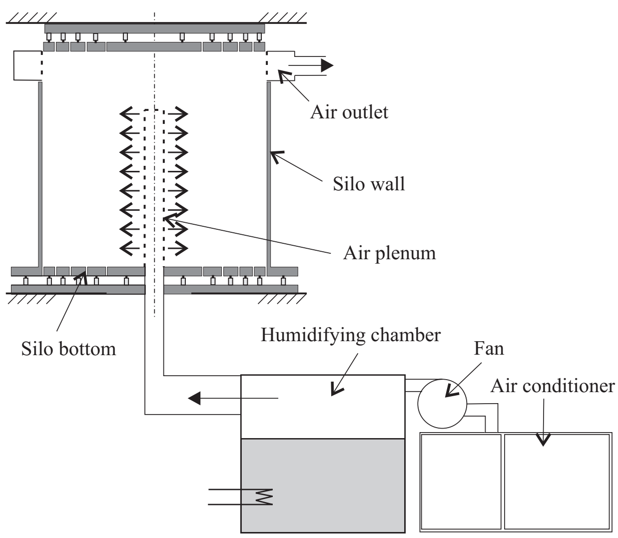

Fig. 3. Model silo with wetting equipment.

The air humidifying system consisted of an air conditioner, a centrifugal fan, a humidifying chamber, and an air plenum that was used to increase moisture content of the grain in the silo. A perforated cylindrical air plenum located centrally in the silo supplied grain with wet air and a perforated circumferential chamber located at upper part of the silo wall was used as the air outlet. Air with relative humidity of up to 95% and the temperature of 36 ^{o}C was blown through the model silo filled with wheat grain.

Temperature and relative humidity of the air in the silo inlet and outlet, change in grain moisture content and swelling pressure exerted on the silo construction were measured during the experiment.

The silo was centrally filled from the filling device located 1.2 m above the silo. The device had a shape of a cone with its vertex directed downward and aligned with the center axis of the silo. Grain was deposited on the pile through an orifice at the vertex of the cone. As a result, the grain formed a conical sloping surface with the vertex directed upwards and the kernels tended to rest with their long axis along the generatrix of the formed cone. After filling, the grain was compacted under the pressure of 10 kPa for 24 h to eliminate contribution of irreversible displacement of grain into the volumetric strain. Bulk density after the pre-compression was 780 kg m^{-3}. Next the vertical pressure was decreased to the value of 3 kPa created by the weight of the top cover of the silo and the height of the bed of grain was fixed. In the last step of the experiment, wet air was blown through the bulk of grain and the swelling pressure was measured. The initial moisture content of the grain u_o was set to about 0.07 to increase the rate of moisture absorption from the ambient air.

RESULTS

Radial distribution of the vertical pressure σ_v on the silo bottom for several values of the moisture content increase is presented in Fig. 4. The vertical pressure increase was the highest near the silo centre and decreased towards the silo wall. This is the result of a decreasing rate of water absorption along the path of air movement. The mean lateral pressure σ_n on the silo wall as influenced by the moisture content increase for two values of the initial moisture content was presented in Fig. 5. The swelling pressure increased linearly with the moisture content increase with the rate of 125 kPa kg kg^{-1}. Comparison of the two experimental relations for very close values of the initial moisture content presented in Fig. 5, indicates that the swelling pressure is strongly influenced by the initial moisture content of grain. Another factor influencing the value of the swelling pressure

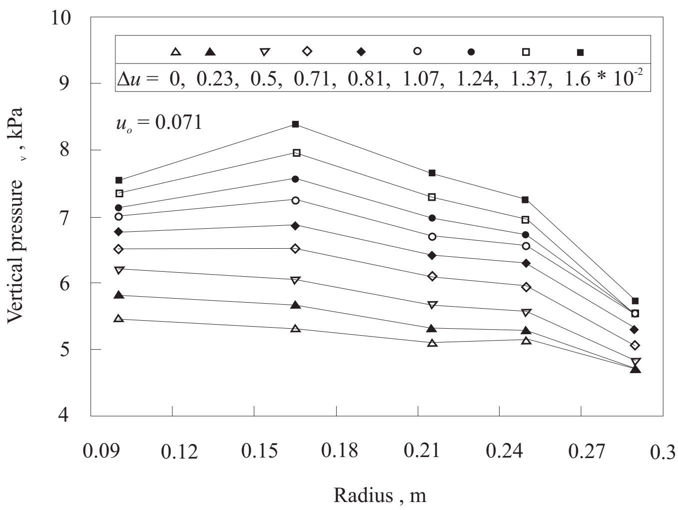

Fig. 4. Radial distribution of vertical pressure σ_v on the silo bottom as influenced by the moisture content increase.

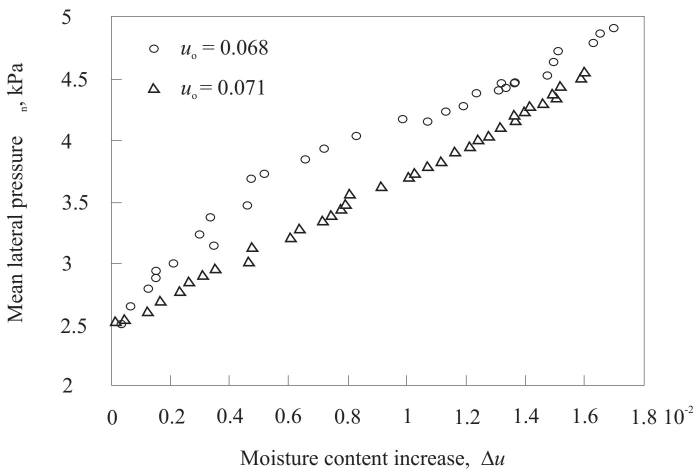

Fig. 5. Mean lateral pressure σ_n on the silo wall as influenced by the moisture content increase.

was bedding structure of the grain created during the filling procedure. The bedding structure influences the pore structure and distribution and, ultimately, permeability of the grain layer. Although the filling procedure was exactly the same in each replication of the experiment, the bedding structure may have differed considerably among replications. This is the most probable reason for a relatively large variation of the swelling pressure values among replications of the test. The initial bulk density was the major factor influencing swelling pressure. The results of the tests performed on the model silo (small precompression - σ_v = 10 kPa, ρ_0=780 kg m^{-3}) as compared to the results of the oedometric test (strong precompression - p=0.5 MPa, ρ_0=835 kg m^{-3} [6]) indicate that the swelling pressure is strongly influenced by the initial compaction of the grain. The rate of swelling pressure increase obtained in the oedometric test was about 30 times higher than the rate of pressure increase obtained in the model silo test for the same range of moisture content increase. The swelling pressure of wetted grain obtained in this study should be treated as a lower limit of a possible swelling pressure increase.

Tangent pressure σ_t on the silo wall decreased linearly with the moisture content increase (Fig. 6). Condensation of water on the silo wall during blowing wet air through the grain decreases the wall friction coefficient. Softening of the kernel seedcoat with an increase in the moisture content is also an important factor leading to a decrease in the tangent pressure. Softening of the seedcoat decreases bulk shear modulus and, consequently, decreases tangent forces at contact points between kernels.

Lateral to vertical pressure ratio as influenced by the moisture content increase was presented in Fig. 7. Initial value of the pressure ratio after filling the model silo was 0.4 and slightly increased during precompression. Unloading of the grain after precompression resulted in an increase in the pressure ratio to about 0.78. Increase in the value of the pressure ratio was the result of the vertical pressure relaxation and not the relaxation of the lateral the pressure due to the rigid silo wall. This value of pressure ratio can be reduced to its initial value during next cycle of loading. Swelling of grain closed in a constant volume can be treated as the next cycle of external loading. According to the Eq. (4), compaction due to external loading and swelling of grain due to water absorption are the two independent components of volumetric strain producing the same effects. Therefore, swelling of grain influences the pressure ratio in a similar

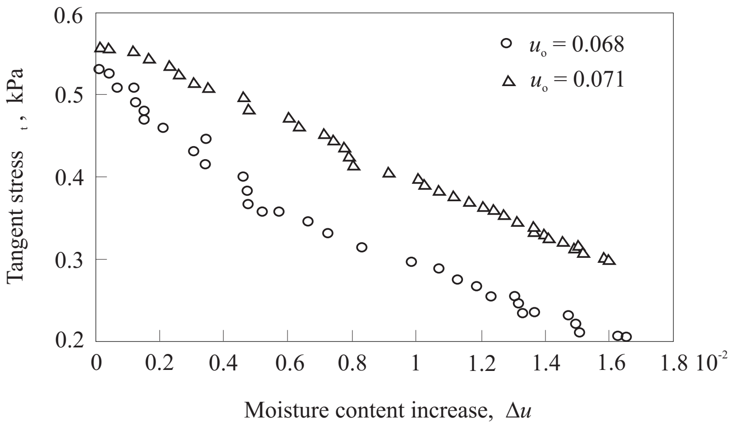

Fig. 6. Tangent pressure σ_t on the silo wall as influenced by the moisture content increase.

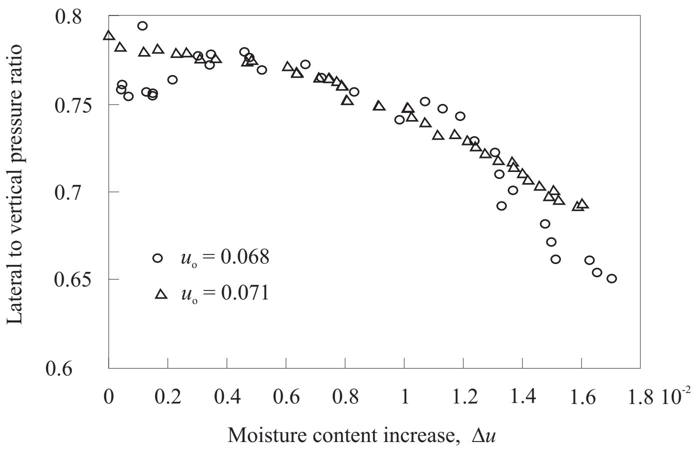

Fig. 7. Lateral to vertical pressure ratio as influenced by the moisture content increase.

way as the next cycle of external loading. The lateral to vertical pressure ratio decreased with the moisture content increase or swelling of grain resulted in faster increase in the vertical rather than the lateral pressure.

The analytical model proposed in this paper is based on two elementary reactions of kernels to water addition: swelling of kernels and decrease in their elasticity with the moisture content increase properly predicts the swelling pressure in the range of the moisture content increase of up to 0.02. This range of the moisture content increase may occur during accidental wetting by ambient air. The model can be used to predict hygroscopic loads in grain storage silos if it is equipped with appropriate experimental values of the effective elastic modulus and shear modulus. Effective elastic modulus of grain in bulk expressed as the power function of confining pressure and decreasing with the moisture content increase reflects real conditions of compression between kernels in contact. From the basic assumptions on the force between spheres in contact accor-ding to the Hertz's theory, it can be concluded that the effective shear modulus of grain in bulk should depend on the moisture content and the confining pressure in the same way as the bulk modulus of grain elasticity. The stress-strain equations for a unit element of grain in bulk may be written in terms of the bulk modulus of elasticity, K, and the effective shear modulus, G:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \left(K - \frac{2}{3}G\right)\varepsilon_v \delta_{ij} \tag{6}$$

where: G - effective shear modulus of grain in bulk (MPa), δ_{ij} - Kronecker symbol, ε_{ij} - strain, σ_{ij} - stress (MPa), and the Eq. (4) relates the confining pressure, p, the moisture content increase, Δu, and volumetric strain, ε_v.

The swelling pressure in the grain silo can be calculated by solving stress equilibrium equations in the lateral and vertical directions. The silo parameters, grain in bulk parameters, swelling model parameters (Eq. (4)) and boundary conditions: wall stiffness (in the lateral direction) and friction of grain against wall (in the vertical direction) are necessary to predict the swelling pressure in a particular case of a grain silo.

SUMMARY

A number of factors, some of which are poorly defined, influence the characteristics of pressure increase during wet air flow through the grain in a silo. This is the reason for the inconsistency of experimental findings reported by various authors. Satisfactory replicability of experimental results requires precise replication of initial conditions such as: grain moisture content, humidity of air passing through the bedding, temperature of passing air and ambient air and spatial structure of bedding. The model proposed in this article allows for the determination of pressure increase in a uniform bedding and strictly established experimental conditions. In such a way, an extreme swelling pressure on the silo structure during grain wetting can be determined. A wide range of load variability, however, can be expected in the practical conditions of a farm silo, where the influencing factors vary in a wide range of values and cannot be accurately controlled.

Swelling pressure of wetted grain is strongly influenced by its precompression history. The maximum value of the swelling pressure of wheat grain obtained after strong precompression (ρ_o=835 kg m^{-3}) was found to be approximately 0.17 MPa and occurred for the moisture content increase of 0.2 [6]. Pressure increase in a range of about 2 kPa for the increase in the moisture content of 0.016 obtained after small precompression of grain in the model silo (ρ_o= 780 kg m^{-3}) presents a lower limit of the swelling pressure. Neither distribution nor value of the swelling pressure is uniform and they depend on the path of wet air movement.

CONCLUSION

Superposition of the two basic reactions of kernels on water absorption, i.e., swelling of kernels and decrease in their elasticity, allows to predict volumetric strain of grain in bulk as a function of confining pressure and moisture content increase. Effective bulk modulus of grain expressed as a power function of confining pressure reflects real conditions of compression between kernels. The model properly describes the swelling pressure in the range of the moisture content increase of up to 0.02. The model can be used to predict hygroscopic loads in grain storage silos if they are equipped with appropriate experimental relations of the effective elastic modulus and shear modulus as the functions of confining pressure and moisture content.

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